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DYNAMICS OF ELLIPTICAL GALAXIES IN THE FRAMEWORK OF MODIFIED NEWTONIAN DYNAMICS

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ABSTRACT

Planetary nebula in elliptical galaxies pose a problem in dark matter theory. Using data from the Planetary Nebula Spectrograph (PN. S), Romanowsky et al. (2003) reported that less dark matter than expected was found within 5 to 6 effective radii of three elliptical galaxies. We attempt to explain similar observations of elliptical galaxies with MOdified Newtonian Dynamics (MOND). We collect 16 elliptical galaxies with planetary nebulae from the public web data of PN. S. We investigate the dynamical behavior by analyzing the line-of-sight velocity dispersion in the framework of MOND.

Key words: Dark Matter - Elliptical Galaxies - MOND - Planetary Nebulae

1. INTRODUCTION

The problem of "missing mass" has been a puzzle in astronomy for a long time. The flat rotation curve of spiral galaxies is widely interpreted as the result of the existence of a dark matter halo which is distributed much more widely than the luminous matter. Dark matter is commonly though to be non-baryonic matter whose existence still eludes detection.

Aside from spiral galaxies, dark matter is also invoked to explain the stellar kinematics (and X-ray observations) of many elliptical galaxies. However, Romanowsky et al. (2003) reported that some luminous elliptical galaxies have little dark matter within 4 to 6 effective radii. This posts a challenge to the ubiquity of dark matter.

The "missing mass" problem is in fact a mismatch between the observed acceleration and the assumed acceleration exerted by the luminous matter of the system through Newtonian dynamics. Instead of unseen matter the discrepancy can be accounted for by modifying the law of inertia or the law of gravity. MOdified Newtonian Dynamics (MOND) proposed by Milgrom (1983) as a modified law of inertia was tailored to this problem. Basically, the theory states that when the acceleration of a particle is smaller than a particular value Newton's second law of motion should be modified. It turns out that thishe theory can be expressed as a modified gravity theory in the form of a nonlinear Poisson equation (Bekenstein & Milgrom, 1984),

$$\nabla \cdot [\tilde{\mu}(|\mathbf{g}|/a_0)\mathbf{g}] = \nabla \cdot \mathbf{g}_\mathrm{N} = -4\pi G\rho\,, \tag{1}$$

where $\mathbf{g}$ is the gravitational acceleration in MOND and $\mathbf{g}_\mathrm{N}$ the gravitational acceleration in Newtonian dynamics. With $x = |\mathbf{g}|/a_0$, $\tilde{\mu}(x)$ is called the interpolation function. It has the asymptotic behaviour $\tilde{\mu}(x) \approx 1$ for $x \gg 1$ (Newtonian regime) and $\tilde{\mu}(x) \approx x$ for $x \ll 1$ (deep MOND regime). The small acceleration scale $a_0 \approx 1.2 \times 10^{-10}$ m s^{-2}. Chiu et al. (2011) suggested a canonical interpolation function of the following form

$$\tilde{\mu}(x) = \left[1 - \frac{2}{(1+\eta x^\alpha) + \sqrt{(1-\eta x^\alpha)^2 + 4x^\alpha}}\right]^{1/\alpha} . \tag{2}$$

Not only does MOND successfully explain the mass discrepancy in spiral galaxies (Sanders & McGaugh, 2002), but also the baryonic Tully-Fisher relation (McGaugh, 2011) in large acceleration mismatch systems. Using X-ray data of elliptical galaxies, Milgrom (2012) found that MOND fitted with the data from NGC 720 and NGC 1521 well, to very large galactic radii (100 and 200 kpc). This corresponds to a wide range of acceleration from more than $10a_0$ to about $0.1a_0$.

Milgrom & Sanders (2003) showed that those luminous elliptical galaxies reported by Romanowsky et al. (2003) belong to small acceleration mismatch systems. In the framework of MOND, it is natural to have a small mass discrepancy in these elliptical galaxies. This is why Newtonian dynamics with luminous matter only works better than a typical dark matter halo model (isothermal mass profile). The results of Milgrom & Sanders (2003) indicated that MOND is close to Newtonian dynamics and fitted the data better.

Kinematic data at large distances from the central part of a galaxy is important for both dark matter scenarios and MOND. As more and more data from PNe at the outskirt of elliptical galaxies are available, it is time to revisit the problem.

2. DATA

The kinematics of early-type galaxies (ETGs) or elliptical galaxies can be studied via stars. However the surface brightness of the stellar component drops rapidly beyond 2 to 3 effective radii and it becomes difficult to measure the stellar velocity dispersion. Unlike late-type galaxies or spiral galaxies, ETGs have little gas content and we cannot rely on gas to study the kinematics at the outskirts of the galaxies. One way to overcome this difficulty is to use planetary nebulae (PNe) because of the strong emission from the O[III] line at 500.7 nm.

Ken Freeman was the first to realize the potential of PNe as a kinematic tracer at the outskirts of galaxies (Gerhard, 2010). The first PN radial velocity in the halo of Centaurus A was measured by Hui et al. (1995) using a multi-fiber instrument at the Anglo-Australian Telescope. The success of the project led to a special-purpose instrument, the Planetary Nebulae Spectrograph (PN.S) mounted at the William Herschel Telescope in La Palma (Douglas et al., 1997).

The PN.S (Douglas et al., 2002) splits the incoming light into two separate cameras and is able to simultaneously measure the position, radial velocity and flux of the PNe in the target galaxies. Since its first light in 2001, PN.S focused on elliptical galaxies and S0, and its data is publicly available in PN.S public web [1]. The PNe catalogue lists position, observed wavelength, heliocentric radial velocity, and magnitude.

In this work, we focus on elliptical galaxies only because we need to model only one component (the stellar content). There are 16 galaxies with available public PNe data posted in the PN.S public web. Among these, 7 are classified as S0, and 3 elliptical galaxies do not have enough PNe data, NGC 3608 ($N_{\mathsf{PNe}} = 91$), NGC 4283 ($N_{\mathsf{PNe}} = 11$) and NGC 3384 ($N_{\mathsf{PNe}} = 93$). Therefore, our sample consists of 6 elliptical galaxies (NGC 5846, NGC 4374, NGC 4494, NGC 3379, NGC 3377, NGC 821). Some of their propertied are listed in Table 1. The PNe line-of-sight velocity distribution of NGC 3379 is illustrated in Figure 1. From the velocity distribution, we compute the velocity dispersion.

3. MODEL

For simplicity, we model the elliptical galaxy as a spherically symmetric stellar system.

3.1. Velocity Dispersion

The velocity dispersion of a spherically symmetric stellar system in equilibrium is governed by the Jeans equation in spherical coordinates (see e.g., Binney & Tremaine, 2008),

$$\frac{d\rho\sigma_r^2}{dr} + \frac{2\beta}{r}\rho\sigma_r^2 = -\rho\, g\,, \tag{3}$$

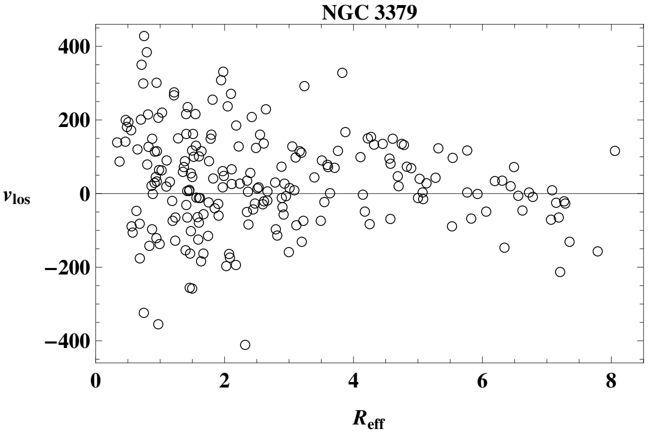

Figure 1. Line-of-sight velocities of 214 PNe of NGC 3379 relative to its galactic centre (data from PN.S public web).

where ρ is the stellar density, $g = -|\mathbf{g}|$ is the gravitational acceleration, σ_r is the velocity dispersion in the radial direction, and the anisotropic function

$$\beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}\,. \tag{4}$$

For an isotropic distribution, $\beta = 0$. The velocity dispersion is then given by (assuming $\rho\sigma_r^2 \to 0$ as $r \to \infty$),

$$\sigma_r^2 = \frac{1}{\rho}\int_r^\infty \rho(r')g(r')\,dr'\,. \tag{5}$$

The velocity dispersion measured along the line-of-sight at projected radius R is given by

$$\sigma_l^2(R) = \frac{2}{I(R)}\int_R^\infty \rho(r')g(r')\sqrt{r^2 - R^2}\,dr'\,, \tag{6}$$

where the surface density is

$$I(R) = 2\int_R^\infty \frac{\rho(r')r'\,dr'}{\sqrt{r'^2 - R^2}}\,. \tag{7}$$

3.2. Mass Model

We adopt a Hernquist profile (Hernquist, 1990) as the mass model for the elliptical galaxies,

$$\rho(r) = \frac{Mr_h}{2\pi r(r + r_h)^3}\,, \quad g_N(r) = \frac{GM}{(r + r_h)^2}\,, \tag{8}$$

where M is the total mass, $r_h \approx 0.55R_{\mathsf{eff}}$, and g_N is the Newtonian gravitational acceleration. Assuming a constant mass-to-light ratio, the surface brightness distribution is the same as the surface density distribution and the effective radius R_{eff} is the same as the half light radius.

3.3. Gravity Model

Instead of Newtonian gravity we use MONDian gravity for the gravitational acceleration g, as described in Section 3.1. In a spherically symmetric system, Equation (1) can be "inverted" as

$$g = \tilde{\nu}(g_{\rm N}/a_0)\,g_{\rm N},\,, \tag{9}$$

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[1] $http://www.strw.leidenuniv.nl/pns/PNS\_public\_web$

Table 1
The sample of elliptical galaxies in this study

Name	Type	D	cz	B_T	N_{PNe}	R_{eff}	R_{LAST}	References
		MPC	km s^{-1}	mag	No.	arcsec	arcmin	
NGC 5846	E0	23.1	1714	10.91	124	53	6	Coccato et al. (2009)
NGC 4374	E1	17.1	1060	10.01	454	53	6.9	Coccato et al. (2009)
NGC 4494	E1	15.8	1344	10.55	267	53	7.6	Napolitano et al. (2009)
NGC 3379	E1	9.8	889	10.18	214	47	7.2	Douglas et al. (2007)
NGC 3377	E5	10.4	665	11.07	154	41	10	Coccato et al. (2009)
NGC 821	E6	22.4	1735	11.72	127	39	6.8	Coccato et al. (2009)

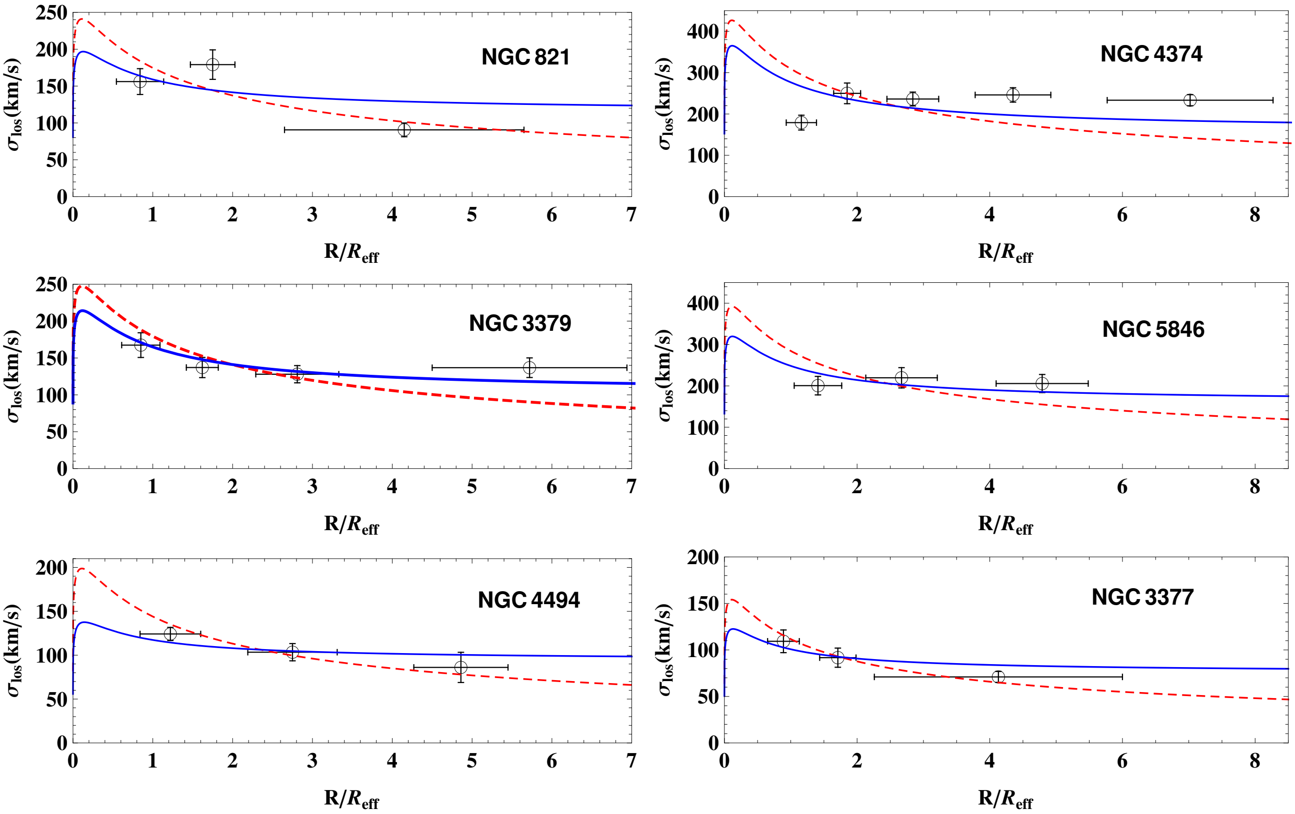

Figure 2. Projected velocity dispersion of the six elliptical galaxies (see Table 1) as a function of the projected radius normalized to R_{eff} of individual galaxy. Open circles are PNe data. We fit the data with Hernquist model. The red dashed line is the best fit in Newtonian dynamics, and the blue solid line is the best fit in MOND in simple form (i.e., $\alpha = 1$, $\eta = 1$ in Equation (2) or (10)).

Table 2
Comparison between Romanowsky et al. (2003) and the latest PNe data

PNe Num	NGC 821	NGC 3379	NGC 4494
Romanowsky et al. (2003)	104	109	73
Latest data on PN.S public web	127	214	267

where $\tilde{\nu}(x_{\text{N}})$ is called the inverted interpolation function. From Equation (2) we obtain the the canonical form for this inverted function (Chiu et al., 2011),

$$\tilde{\nu}(x_{\text{N}}) = \left[1 + \frac{1}{2}\left(\sqrt{4x_{\text{N}}^{-\alpha} + \eta^2} - \eta\right)\right]^{1/\alpha}, \qquad (10)$$

where $x_{\text{N}} = g_{\text{N}}/a_0$. We note that g and g_{N} are positive in our formulation.

4. RESULTS

In the dark matter halo scenario one expects that dark matter becomes more significant compared with ordinary matter when the location is further away from the central part of a galaxy. Observations at the outskirts of galaxies is crucial in this respect. We use PN.S data to trace the dynamics at the outskirts of six elliptical galaxies (see Table 1). As a test of the alternative view on the "missing mass" problem, we fit the data with MOND. We adopt a spherically symmetric Hernquist mass model for the galaxies and choose a simple form for our interpolation function (i.e., the form of modified gravity)

$$\tilde{\mu}(x) = \frac{x}{(1+x)}\,, \tag{11}$$

where $x = g/a_0$, i.e., $\alpha = 1$, $\eta = 1$ in Equation (2) and the corresponding inverted interpolation function

$$\tilde{\nu}(x_{\rm N}) = \frac{1}{2} + \sqrt{\frac{1}{x_{\rm N}} + \frac{1}{4}}\,. \tag{12}$$

In this formulation, we have only one parameter, M, the mass of the galaxy. We fit our model to the data and the result is shown in Figure 2.

The three galaxies (namely, NGC 821, NGC 3379, and NGC 4494) in Romanowsky et al. (2003) also appear in our sample, but there are more PNe data now (see Table 2). Nonetheless, our result is consistent with Romanowsky et al. (2003); Milgrom & Sanders (2003). Moreover, analysis of the other three galaxies (NGC 4374, NGC 5846, NGC 3377) produces a similar conclusion to Romanowsky et al. (2003), i.e., Newtonian dynamics can explain the velocity dispersion outside 2 $R_{\sf eff}$ without invoking dark matter. This runs counter to the tenets of dark matter halo models, which are supposed to have more dark matter at the outer part of galaxies. For example, NGC 3379 has been argued to be "naked", i.e., lacking a significant dark matter halo (see e.g., Romanowsky et al., 2003; Douglas et al., 2007). On the other hand, using radically anisotropic orbit distributions, de Lorenzi et al. (2009) employed the made-to-measure particle code NMAGIC (de Lorenzi et al., 2007) and showed that some dark matter halo is still needed.

A Hernquist model in MOND fits the data well (see Figure 2), and the mass of the galaxies is about 28-58% smaller than those obtained by Newtonian dynamics. The difference in mass is small and comes from the fact that the "effective acceleration" is large compare with a_0, the acceleration scale of MOND.

In spiral galaxies the parameter

$$\xi = \frac{V_\infty^2}{R_{\sf eff}\, a_0}\,, \tag{13}$$

has been use to distinguish two types of spirals: (i) high surface brightness (HSB) spirals and (ii) and low surface brightness (LSB) spirals. In the framework of dark matter, HSB spirals require less dark matter and LHS spirals more. In the framework of MOND, xi tells us the whether the system is more like a Newtonian system (HSB, larger ξ) or a MONDian system (LSB, lower xi). For example, NGC 2903, an HSB spiral, has $\xi \sim 2.5$, while NGC 1560, an LSB spiral, has $\xi \sim 0.5$ (a dwarf spheroidal can be as small as $\xi \sim 0.1$) (e.g. Milgrom & Sanders, 2003).

Table 3
THE PARAMETER ξ AND MASS M (IN 10^{10}M$_\odot$) OF OUR SAMPLE

Name	ξ	$M_{\sf Newton}$	$M_{\sf MOND}$
NGC 821	2.1	28.0	17.5
NGC 3379	3.1	15.6	11.3
NGC 4494	1.0	18.3	7.7
NGC 4374	2.8	91.1	65.4
NGC 5846	2.2	104.2	66.7
NGC 3377	0.8	5.6	3.3

Masses are obtained from the best fit of PNe velocity dispersion data with Hernquist mass distribution in Newtonian dynamics and MOND.

For the six elliptical galaxies in our sample, ξ can be estimated from V_∞ of Coccato et al. (2009). We list ξ and the mass (from Newtonian dynamics and MOND) in Table 3. All galaxies, except NGC 3377 ($\xi = 0.8$), have a ξ larger than unity ($\xi = 1.0 \sim 3.1$), and are therefore HSB spiral galaxies. As a large ξ corresponds to a more Newtonian-like system we do not expect the difference in masses found by Newtonian dynamics and MOND to be large. This is what we found, as shown in Table 3.

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